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FLY ASH AS A MINERAL FILLER AND ANTI-STRIP AGENT FOR ASPHALT CONCRETE

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16. Abstract

This project studied the effectiveness of fly ash and other filler-additives as replacements for portland cement and hydrated lime in production of asphalt concrete mixtures. Both mixture design and moisture resistance characteristics were studied. Properties of asphalt concrete containing additions of two different fly ashes at 1, 3, and 6 percent; four combinations of cement, lime, and fly ash; lime kiln dust at 2 percent; and residue from a pilot copper extraction process at two levels, were compared to those of mixtures containing only natural fines; a chemical anti-strip; 2 percent hydrated lime; and 2 percent portland cement.

Results of the mixture design phase indicate that with respect to Marshall mixture design criteria, acceptable asphalt concrete mixtures can be produced in the laboratory with up to 6 percent fly ash by weight of aggregate. Differences noted with mixtures containing up to 6 percent fly ash were (1) reduced asphalt requirements and (2) lowered V.M.A. values.

Analysis of data generated during immersion-compression testing indicates that fly ash and other fillers investigated in this study can improve moisture resistance characteristics of asphalt concrete mixtures in the laboratory. Several of the filler additives investigated in this study were found to be as effective for improving moisture resistance as chemical anti-strip, portland cement, and hydrated lime.

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INDEX

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PROJECT PERSONNEL

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1.0 INTRODUCTION

1.1 Certain aggregates have a greater affinity for water than for asphalt. In the case of asphalt-aggregate mixtures, if sufficient moisture is present, water may intrude between the aggregate and asphalt coating resulting in loss of adhesion. This is referred to as stripping or water sensitivity and can result in premature pavement deterioration and failure.

Measures to reduce water sensitivity of asphalt-aggregate mixtures include the use of dense graded mixtures to aid in reducing the amount of water which can enter into the mixture; addition of chemical anti-strip agents to the bituminous binder; spray treatment of stockpiled aggregates with lime slurry or other chemicals; and the addition of dry lime or portland cement to the mixture. Choice of a particular treatment is based on laboratory testing of the aggregate-binder combination to be used, local experience, and economics.

1.2 Problem Statement In many sections of Arizona, addition of either portland cement or hydrated lime to asphalt concrete mixtures is required to produce pavements with acceptable resistance to stripping. Cement or lime is usually added in amounts varying between 1/2 and 2 percent by weight of mix. These additions of cement or lime can increase mixture costs up to approximately 10 percent. Increased costs of cement and lime and the recent shortage of cement suggest that other anti-strip treatments be considered to reduce cost of asphalt concrete mixture production while maintaining satisfactory resistance to stripping.

1.2.1 The mechanisms of cement and lime treatments are not fully understood, but it is postulated that available calcium in the materials imparts beneficial anti-strip characteristics (1)*. Limited available information suggests that additions of fly ash to asphalt concrete mixtures may aid in improving moisture resistance. This is due to two properties of fly ash:

- The physical characteristics of fly ash are such that it can function as a mineral filler providing increased mixture density, reinforcement and stiffening of the binder, and reduction of mixture permeability.

- The presence of available calcium.

1.2.2 Advantages which could be realized by successful use of fly ash as a replacement for cement or lime in asphalt concrete mixtures are:

- Decreased mixture costs due to lower costs of fly ash when compared to cement or lime.

*Numbers in parenthesis indicate references at end of text.

- Reduced demand for non-renewable resources of cement and lime and savings in energy required for production.

- Use of a by-product from combustion of coal.

1.3 Objective The objective of this investigation is to develop data necessary to establish the efficiency of fly ash as a partial or total substitute for portland cement or hydrated lime in asphalt concrete. This objective was attained by:

- Conducting a review of previous work related to usage of fly ash as a mineral filler in asphalt concrete, and

- Conducting a statistically designed factorial experiment which examined the effect of fly ash and conventional anti-strip treatments on mixture properties.

1.3.1 Additionally, the study investigated two other types of treatments - KD-30 (lime kiln dust) and clear plant residue (residue from a pilot copper extraction process). Funding required for inclusion of these materials was obtained independently from the original contract.

2.0 CONCLUSIONS AND RECOMMENDATIONS

2.1 Mixture Designs

2.1.1 Results obtained during the mixture design phase of this investigation indicate that, with respect to Marshall mixture design criteria, acceptable asphalt concrete mixtures can be produced in the laboratory with up to 6 percent fly ash by weight of aggregate. Differences which may exist in asphalt concrete mixtures with up to 6 percent fly ash are:

- Reduced asphalt requirements

- V.M.A. values

Determination of fatigue characteristics of mixtures containing fly ash was beyond the scope of this study, but should be investigated.

2.2 Immersion-Compression Testing

2.2.1 Data obtained during the immersion-compression testing phase of this investigation yielded information on the effectiveness in the laboratory of fly ash and other fillers as anti-stripping additives in comparison to additives currently being used; portland cement, hydrated lime and Pave Bond Special. Filler-additives which were found to be most effective for improving stripping resistance of asphalt concrete mixtures in the laboratory were:

- Clear Plant Residue (CPRL, CPRH)
- Pueblo Fly Ash (3P, 6P)
- Navajo Fly Ash (6N)
- Combination of Hydrated Lime and Navajo Fly Ash (1L5N)

Several of the filler-additives investigated performed as well in the laboratory as portland cement, hydrated lime and Pave-Bond Special including:

- Clear Plant Residue (CPRL, CPRH)
- Pueblo Fly Ash (1P, 3P, 6P)
- Navajo Fly Ash (1N, 3N, 6N)
- Lime Kiln Dust (2KD)
- Combinations of Cement, Lime and Fly Ash (1L5N, 1L2P, 1/2C5N, 1/2C2P

Use of these filler-additives as anti-stripping treatments for asphalt concrete pavements should be further considered.

2.2.2 Analysis of variance showed that filler-additive effectiveness as anti-stripping agents varied for the aggregates and mixes investigated and that aggregate-mixture interactions existed, indicating that the effectiveness of filler-additives to be used as anti-stripping agents needs to be determined for individual asphalt concrete mixtures.

2.2.3 Air void levels and densities of immersion-compression test specimens were found to be different from values obtained during mixture designs and found to vary between mixtures. It is believed that these variations may influence percent retained strength and wet compressive strength results obtained during testing. Consideration of the effects of air voids and densities on immersion-compression test results should receive further attention.

3.0 LITERATURE REVIEW

3.1 The Stripping Problem

3.1.1 Stripping of asphalt from aggregate surfaces can result from several factors and may cause varying degrees of pavement distress. It is believed that the most important factor which leads to stripping is the presence of moisture in voids of the asphalt mixture (2). It has also been noted that added effects of traffic loadings and freeze-thaw cycles may be required to initiate stripping (3, 4). Additionally, both physical and chemical properties of aggregates and asphalt have been found to influence the water resistance of asphalt concrete mixtures. Pavement distress resulting from stripping can range from minor damage to complete structural failure of the asphalt concrete surfacing. Damage usually occurs as ravelling, subsequent formation of potholes, and loss of structural stability.

3.2 Materials Properties Which May Influence Stripping

3.2.1 Many materials properties of asphalt concrete pavements have been found to influence the stripping problem, including mixture permeability, aggregate characteristics, and binder characteristics.

3.2.1.1 Mixture Permeability Pavements with high air voids have been found to be more susceptible to stripping than ones with lower air voids (3, 5). Pavements with high air voids are more permeable and will allow greater amounts of moisture to enter into the void system of the asphalt concrete mixture than will pavements with lower air voids.

3.2.1.2 Aggregate Characteristics Both physical and chemical properties of aggregates can influence the stripping problem including:

- Mineralogic composition (5)
- Surface Texture (5)
- Coatings (5)
- Degree of weathering (6)
- Surface energy (5)
- Particle shape (5)
- Porosity (5)
- Abrasion resistance (7)

These properties influence either the

quality or completeness of the asphalt-aggregate adhesive bond or the ease with which water may intrude between the asphalt and aggregate.

3.2.1.3 Asphalt Characteristics Both physical and chemical characteristics of asphalts influence the stripping problem (8). Asphalts of higher viscosity have been noted to be more resistant to stripping than lower viscosity asphalts (8). Chemical composition of asphalts, as related to crude source and refining process, has also been found to possibly influence the stripping problem (8, 9).

3.3 Anti-Strip Additions and Treatments

3.3.1 Several different types of anti-strip additives and treatments have been successfully used to improve the moisture sensitivity of asphalt concrete mixtures. Two different methodologies have been followed. First, mixture permeability can be decreased by increasing asphalt content, increasing degree of compaction, or by adding fillers which aid in decreasing air voids. These types of mixture modifications aid in reducing the amount of moisture which can enter into voids in the pavement. The second methodology which has been used is to treat the aggregate, asphalt, or both with an admixture that will improve the asphalt aggregate bond. Types of treatments which have been successfully used include surface active asphalt additives, surface active aggregate additives, and fillers including hydrated lime and portland cement.

3.1.1.1 Surface Active Asphalt Additives These types of anti-strip additives generally consist of a non-polar hydrocarbon chain with a polar end (usually an amine) (10). Addition of one-half to one percent additive by weight of asphalt can result in improved moisture resistance due to reduced surface tension of the asphalt, resulting in an improved asphalt-aggregate bond. Another benefit of these types of additives is their ability to form a physico-chemical link between the asphalt and aggregate. The non-polar hydrocarbon end is attracted to the asphalt and the polar end to the aggregate. Surface active asphalt additives are presently used quite effectively on a widespread basis with many different mixture and aggregate types.

3.3.1.2 Surface Active Aggregate Additives These types of anti-strip additives generally consist of heavy metal soaps which when dissolved in water and applied to aggregates result in deposition of metal cations on aggregate surfaces (11). Aggregates treated with metal cations have been found to have improved resistance to stripping. Presently, these types of treatments are not widely used.

3.3.1.3 Hydrated Lime Hydrated lime has been added to asphalt concrete mixtures in order to improve stripping resistance for many years (12). Additions between one and two percent have, in many cases, improved stripping resistance quite effectively (13). Lime may be added as a filler but has been found to be more effective if applied to stock-piled aggregates in slurry form and allowed to cure for several days. The mechanism by which hydrated lime improves stripping resistance is not known, but is believed to be related to interactions between free calcium in the lime and the asphalt or aggregate.

3.3.1.4 Portland Cement As with hydrated lime, one to two percent additions of portland cement have been used quite effectively for improving stripping resistance of asphalt concrete mixtures. Cement is added as a filler. Again, as with hydrated lime, the mechanism by which portland cement improves stripping resistance is not known.

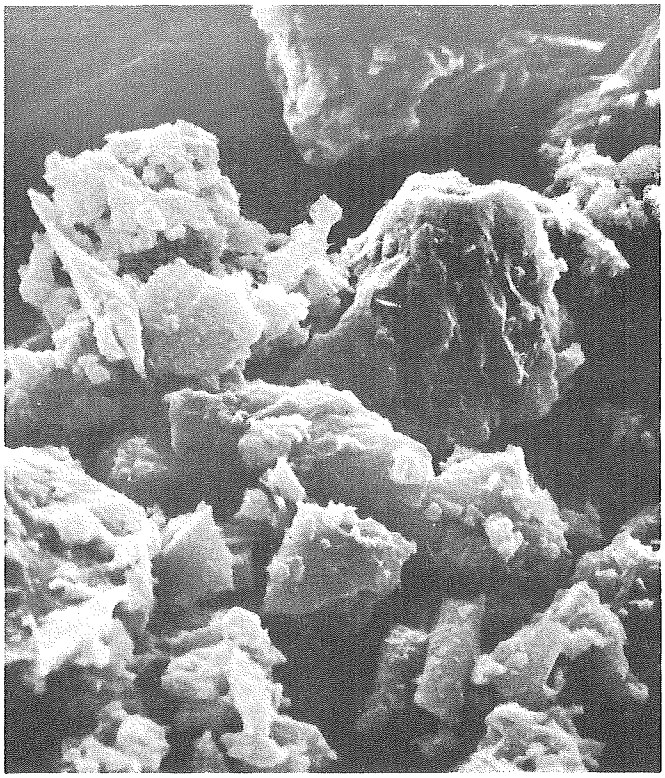
3.3.1.5 Fly Ash "Fly ash is a by-product of the combustion of coal and is usually associated with power plants which burn fossil fuels. Fly ash is a very fine, light dust which is carried off in the stack gases from a boiler unit and collected by mechanical or electrostatic methods. It is derived primarily from rock detritus which collects in the fissures of coal seams (14), and constitutes 8 to 14 percent of the weight of the coal (15). Fly ash should not be confused with bottom ash, a granular by-product which drops to the bottom of the boiler unit and is occasionally mixed and stored with fly ash." (16)

Several citations exist in the literature regarding the use of fly ash as a mineral filler in asphalt concrete mixtures. Fung (17) reported on the use of fly ash in asphalt concrete roads in New South Wales as a replacement for limestone dust fillers. It was determined in laboratory studies that fly ash could be used to produce acceptable asphalt concrete mixtures and that fly ash imparted better stripping resistance to mixtures than did limestone dust. In 1962, the New South Wales Department of Main Roads began using fly ash as a mineral filler in asphalt concrete pavements at a substantial cost savings over previous fillers.

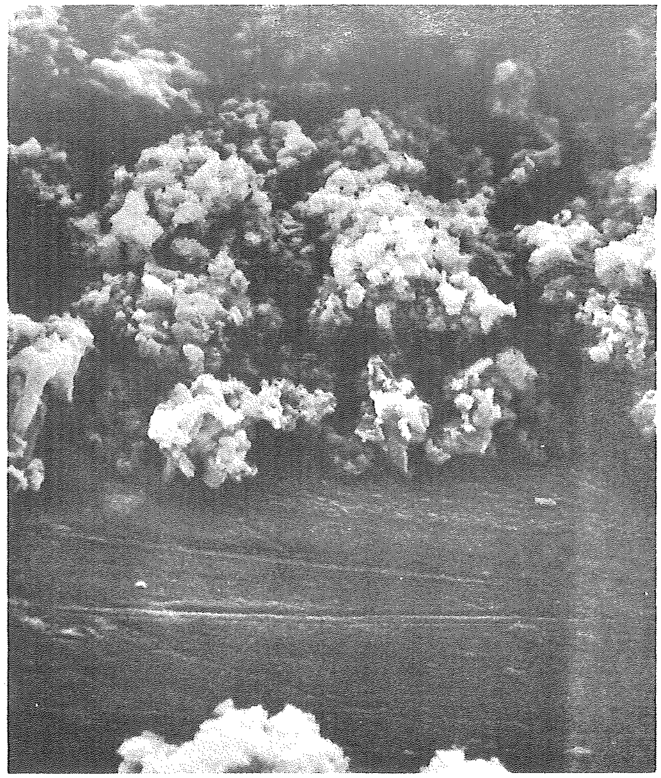
Brahma (18) reported on a laboratory investigation which considered the use of fly ash derived from lignite coal in asphalt concrete mixtures. He found that mixtures containing fly ash as a filler could be prepared which would meet required Marshall mixture design criteria. The study also found that retained compressive strengths of specimens containing fly ash tested in accordance with ASTM Method of Test D 1075, "Effect of Water on Cohesion of Compacted Bituminous Mixtures", were much higher than those of comparable specimens containing crusher dust as a filler, but not as high as specimens containing hydrated lime. This suggests that the lignite fly ash investigated possessed qualities desirable in an anti-strip additive.

Zimmer (19) reported on laboratory studies which investigated the use of fly ash in comparison to other mineral fillers in asphalt concrete. Based on mixture design and water resistance data, it was concluded that fly ash appears to be satisfactory as a mineral filler in asphalt concrete mixtures.

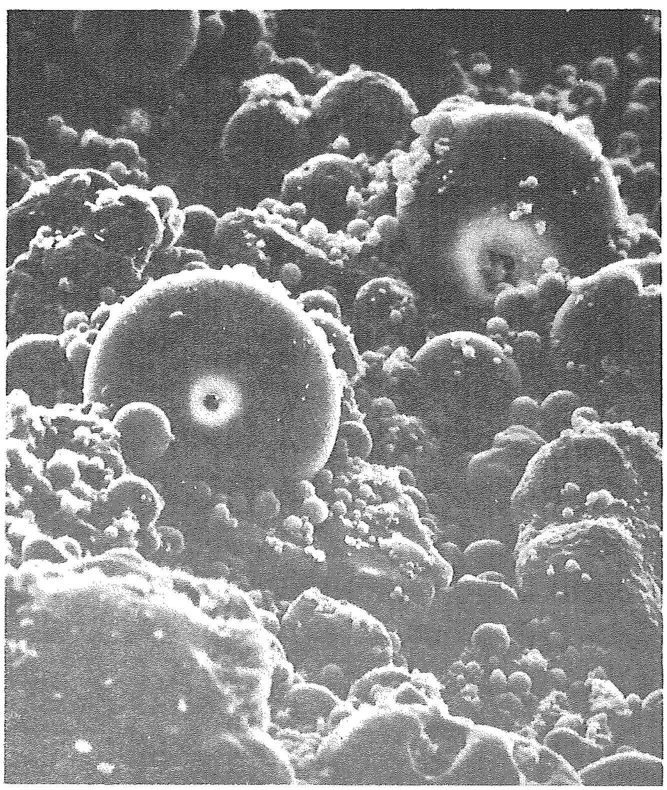
Some reasons for considering fly ash as a replacement filler for portland cement or lime can be seen by referring to Figure 1. Scanning electron photomicrographs are used to compare the three materials. Two items that are of special interest are particle shape and size-surface area of the three materials. Fly ash appears to be a well-graded material which would indicate a good probability of increased density by virtue of packing progressively smaller particles into voids of the filler. This increased density should improve watertightness of asphalt mixtures and hence decrease water sensitivity of the mixture. Increased density and reduced permeability should be further enhanced by the spherical shape of fly ash particles. The same improved workability due to sphericity of fly ash that is observed in portland cement concretes should occur in asphalt mixtures, admittedly to a lesser degree because of the lower relative volume of fly ash in asphalt mixtures, but nonetheless a factor worth consideration. It can be further hypothesized that the relatively smooth surface texture of



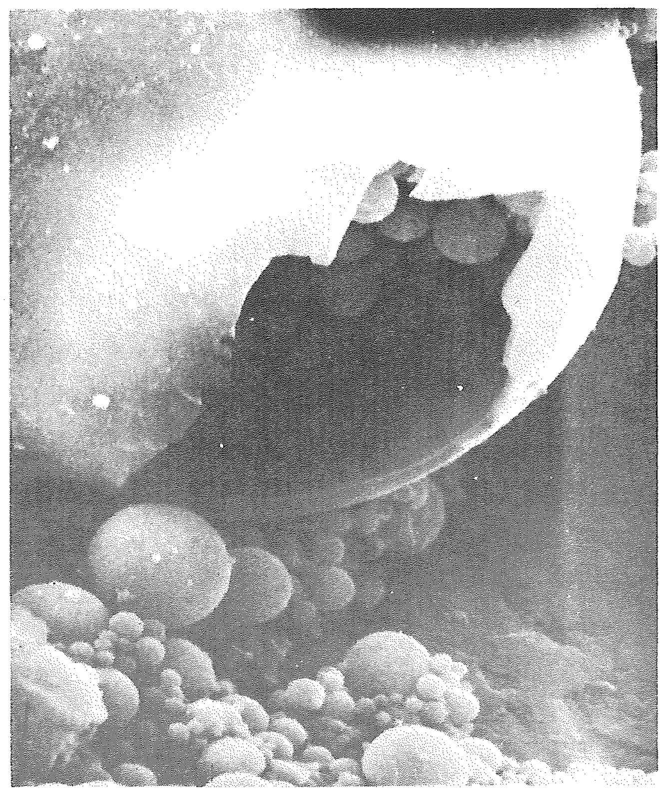
3000X 45° Tilt Portland Cement 3.3 µM



3000X 45° Tilt Lime 3.3 µM



1000X 45° Tilt Fly Ash 10 µM



3000X 45° Tilt Fly Ash 3.3 µM

Figure 1
Scanning Electron Photomicrographs

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fly ash, as compared to lime or portland cement, would have a lower asphalt demand than equivalent volumes of lime or portland cement since binder demand is highly sensitive to surface area of the finer aggregate.

Chemical analysis of local fly ash shows significant levels of calcium but x-ray diffraction measurements made during the scanning electron microscope study did not detect free lime or other calcium materials. This observation would indicate that physical properties of fly ash may be the controlling mechanism in contributing to the anti-strip characteristics. Whatever the mechanism, decreased water sensitivity of asphalt mixtures containing fly ash has been observed and measured in some hydraulic and airport paving materials (20).

Based on the desired qualities of an anti-strip additive, properties and characteristics of fly ash, and previous studies which investigated the use of fly ash in asphalt concrete, it seems that additions of certain fly ashes may be effective for improving the stripping resistance of asphalt concrete mixtures.

4.0 MATERIALS INVESTIGATED

4.1 Aggregates

This study was designed to investigate the properties of asphalt concrete mixtures made with aggregates from two commercial sources - one which usually does not require addition of anti-strip additives to produce acceptable mixtures, and one which does. Salt River aggregate was chosen as the source which usually does not require anti-strip treatments. Aggregate from the Cottonwood Wash Pit (Reidhead) in Taylor, Arizona was chosen as the source which requires anti-strip additives.

During the course of the investigation, it was found that the Reidhead source was not responding favorably to anti-stripping treatments being investigated and was yielding information which would not be of use in statistical analyses. Therefore, a third aggregate source was investigated as a replacement for the Reidhead source. The third aggregate investigated was from a commercial pit in the Agua Fria River. Though not used in analyses in this report, data obtained for mixtures containing Reidhead aggregate are presented for reference.

The problem with the Reidhead aggregate is believed to have been caused by a dusty coating on its coarse fractions. Dry sieving indicated that 4 percent of the aggregate was finer than the No. 200 (75-μm) sieve, but a washed sieve analysis of a sample of material graded according to mixture design proportions indicated that 16 percent was finer than the No. 200 (75-μm) sieve. The extra 12 percent fines were present as a dust coating. Dust coatings have been found to be a cause of moisture sensitivity, as previously discussed. (Section 3.2.1.2).

4.1.1 Aggregates used in the study were obtained and processed into various size fractions by the Research Section of ADOT.

4.1.2 Results of specific gravity and absorption determinations for aggregates used in this study are tabulated in Table 1.

4.1.3 Aggregate Descriptions

4.1.3.1 Salt River (United Metro) - homogeneous, siliceous, well rounded crushed river gravel.

4.1.3.2 Agua Fria (Industrial) - homogeneous, siliceous, well rounded crushed river gravel.

4.1.3.3 Cottonwood Wash (Reidhead) - heterogeneous, siliceous, dust coated crushed gravel containing sandstone and quartzite particles.

4.2 Asphalt

Asphalt used in the study was an AR-2000, obtained from Sahuaro Petroleum and Asphalt Company, Phoenix, Arizona.

Table 1. Specific Gravities and Absorptions of Aggregates Investigated

Source	Fraction	Specific Gravity Bulk	Specific Gravity Bulk SSD	Specific Gravity Apparent	% Absorp.
Salt River	+#4 (1)	2.637	2.671	2.735	1.40
	-#4 (2)	2.612	2.661	2.747	1.90
	-#200 (3)	2.710	_____	2.710	_____
Agua Fria	+#4	2.542	2.579	2.640	1.45
	-#4	2.491	2.543	2.629	2.10
Reidhead	+#4	2.531	2.576	2.651	1.79
	-#4	2.491	2.585	2.750	3.78
	-#200	2.827	_____	2.827	_____

Notes:

(1) ASTM C 127-77
(2) ASTM C 128-73
(3) ASTM D 854-58

4.2.1 Viscosity at 140°F(60°C), viscosity at 275°F(135°C) and penetration at 77°F(25°C) tests were performed on a sample of the asphalt which was subjected to ASTM D 2872-77. The following tests were conducted on the aged residue:

- 140°F(60°C) Viscosity - ASTM D 2171-78, "Viscosity of Asphalts by Vacuum Capillary Viscometer".

- 275°(135°C) Viscosity - ASTM D 2170-76, "Kinematic Viscosity of Asphalts (Bitumens)".

- 77°F(25°C) Penetration - ASTM D5-49, Penetration of Bituminous Materials".

Test results are tabulated in Table 2. The asphalt meets ADOT requirements for an AR-2000 asphalt cement.

4.3 Chemical Anti-Strip Agent

4.3.1 The chemical anti-strip agent used in the study was Pave Bond Special supplied by Arizona Refining Company. One percent additions by weight of asphalt cement were used in this study.

4.4 Fillers

Seven different fillers were studied as possible anti-strip agents:

Table 2 Physical Properties of AR-2000 Asphalt Cement

Property	Before Aging	After* Aging
Penetration, 77.0°F, 100gm 5 sec; 1/10 mm	82	52
Viscosity, 140°F, 30cm Hg Poise	-	2324
Viscosity, 275°F; cSt	-	291

*Tests on residue from rolling thin film over test.

- Natural fines - supplied with the aggregates.

- Portland cement - Phoenix, Type II, Phoenix Cement Co.

- Hydrated lime - Type N, U. S. Lime, Flintkote Division, Henderson, Nevada.

- Navajo fly ash - Navajo Power Plant, Page, Arizona.

- Pueblo fly ash - Comanche Power Plant, Pueblo, Colorado.

- Kiln dust - KD-30 lime kiln dust, from Paul Spur Lime Company, supplied by Western Ash Company.

- Clear plant residue - residue from a pilot copper extraction process.

4.4.1 Physical and chemical analyses were performed on samples of Navajo fly ash, Pueblo fly ash, and kiln dust. Results are tabulated in Tables 3 and 4. From Table 4, it can be seen that kiln dust has a higher calcium oxide content than either the Pueblo or Navajo fly ashes which, as previously discussed (Section 3.3.1.3), may be related to effectiveness as an anti-strip agent.

Table 3. Physical Analysis of Navajo Fly Ash, Pueblo Fly Ash and Kiln Dust

Determination	Navajo Fly Ash	Pueblo Fly Ash	Kiln Dust
	Results		
Specific Gravity	2.339	2.699	2.899
Retained on No.325;%	23.3	18.3	84.3
Water requirement; %	94	98	108
Pozz. Act. w/P.C.			
7 day; %	80	79	42
28 day; %	88	79	50
Pozz. Act. w/lime;psi	921	835	477
Autoclave soundness;%	0.06	0.01	*
Drying shrinkage;%	-0.02	-0.004	-0.01
Alkali-reactivity			
Mortar exp.red.	28	58	2.0
Multiple factor	11	41	____

*Bars expanded beyond range of comparator.

Table 4. Chemical Analysis of Navajo Fly Ash, Pueblo Fly Ash and Kiln Dust

Determination	Results: Navajo Fly Ash	Pueblo Fly Ash	Kiln Dust
Silicon Dioxide, SiO_2; %	53.68	49.16	17.08
Aluminum Oxide, Al_2O_3; %	24.25	13.82	6.76
Ferric Oxide, Fe_2O_3; %	3.47	5.77	6.34
Total; %	81.40	68.75	30.18
Sulfur Trioxide; SO_3; %	0.86	5.60	2.40
Calcium Oxide, CaO; %	6.18	24.74	53.43
Magnesium Oxide, MgO; %	1.54	0.84	0.70
Moisture; %	0.01	0.07	0.02
Loss On Ignition; %	0.47	0.66	11.60
Alkalies (Na_2O+0.658K_2O), Na_2O; %	1.23	2.24	0.52

4.4.2 Clear plant residue is a residue from a pilot copper extraction process. The material is composed of fine mineral particles coated with sulfur. Sulfur content of residue used in this study was 20 percent. Following extraction of sulfur, 100 percent of the residue was finer than a No. 50 (300-μm) sieve, 96 percent was finer than a No. 100 (150-μm) sieve, and 81 percent was finer than a No. 200 (75-μm) sieve. The specific gravity of the clear plant residue, after extraction of sulfur, was found to be 3.054 (ASTM D 854-58).

Additions of clear plant residue to hot-mix asphalt concrete result in the formation of sulfur-extended asphalt as a result of the sulfur in the residue combining with asphalt during mixing (21). Information on properties of sulfur-extended asphalt mixtures has been reported elsewhere (22, 23).

Two levels of sulfur replacement were investigated - low and high. The low replacement level resulted in the formation of a 25 percent by weight sulfur-extended asphalt and the high a 35 percent sulfur-extended asphalt.

4.5 Mixtures Investigated

Seventeen different mixture combinations were investigated with Salt River and Agua Fria aggregate. Eleven different combinations were investigated with Reidhead aggregate.

4.5.1 Mixture designations are as follows:

Mixture	Designation
Salt River Aggregate	SR
Agua Fria Aggregate	AF
Reidhead Aggregate	RH
Natural Fines	NF
Pave-Bond Special	PB
Portland Cement	C
Hydrated Lime	L
Navajo Fly Ash	N
Pueblo Fly Ash	P
Kiln Dust	KD
Clear Plant Residue, low replacement	CPRL
Clear Plant Residue, high replacement	CPRH

4.5.2 Mixture combinations investigated in this study are shown in Figure 2. Numbers which precede letter designations indicate filler-additive percentages by weight of aggregate.

Figure 2. Mixture Combinations Investigated

Aggregate Source / Mix Designation	NF	PB	2C*	2L	1N	3N	6N	1P	3P	6P	½C5N	½C2P	1L5N	1L2P	2KD	CPRL	CPRH
SALT RIVER	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
AGUA FRIA	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
REIDHEAD	X	X	X	X	X	X	X	X	X						X		

*Note: Numbers preceding letter designations indicate percent addition by weight of aggregate

5.0 LABORATORY INVESTIGATION

The laboratory investigation consisted of performing mixture designs for each mixture combination and then selecting a design asphalt content to be used in specimens used for immersion-compression testing. Mixture designs and immersion-compression tests were performed at random for mixtures made with each aggregate source.

5.1 Mixture Designs

5.1.1 Mixture designs were performed in accordance with the Marshall method outlined in The Asphalt Institute Publication MS-2 (24). One mixture design, using triplicate specimens at four asphalt contents, was performed for each mixture combination. A total of 45 designs were performed.

5.1.2 Mixtures were proportioned as dense-graded asphalt concretes with a 1 in. maximum nominal particle size.

Gradations used in this study for mixes from each aggregate source were specified by ADOT.

Gradations of mixtures with filler-additive contents investigated are tabulated in Tables 5, 6, and 7 and plotted in Figures 3, 4, and 5.

Table 5. Gradations of Salt River Aggregate used in Study with 0, 1, 2, 3, and 6% Added Filler

	% Passing with Indicated % Filler				
Sieve Size	0%	1%	2%	3%	6%
1"	100	100	100	100	100
3/4"	90	90	90	90	91
1/2"	74	74	75	75	76
3/8"	66	66	67	67	68
1/4"	56	57	57	57	59
#4	53	54	54	54	56
#8	43	44	44	45	46
#10	40	41	41	42	44
#16	31	32	33	33	35
#30	21	22	23	23	26
#40	16	17	18	19	21
#50	11	12	13	14	16
#100	6	7	8	9	12
#200	4	5	6	7	10

Table 6. Gradations of Agua Fria Aggregate used in Study with 0, 1, 2, 3, and 6% Added Filler

	% Passing with Indicated % Filler				
Sieve Size	0%	1%	2%	3%	6%
1"	100	100	100	100	100
3/4"	97	97	97	97	97
1/2"	75	75	76	76	76
3/8"	65	65	66	66	67
1/4"	48	49	49	50	51
#4	44	45	45	46	47
#8	37	38	38	39	41
#10	35	36	36	37	39
#16	30	31	31	32	34
#30	20	21	22	23	25
#40	16	17	18	18	21
#50	12	13	14	15	17
#100	7	8	9	10	12
#200	5	5	7	7	10

Table 7 Dry and Washed Gradations of Reidhead Aggregate Used in Study with 0, 1, 2, 3, and 6% Added Filler

	% Passing with Indicated % Filler									
	0%		1%		2%		3%		6%	
Sieve Size	Dry	Wash	Dry	Wash	Dry	Wash	Dry	Wash	Dry	Wash
1"	100	100	100	100	100	100	100	100	100	100
3/4"	94	95	94	95	94	95	94	95	94	95
1/2"	71	75	71	76	71	76	72	76	73	76
3/8"	59	64	59	64	60	65	60	65	61	66
1/4"	50	56	51	56	51	51	52	51	53	59
#4	44	51	45	51	45	52	46	52	47	54
#8	38	46	39	46	39	47	40	47	41	49
#10	37	45	38	45	38	46	39	46	41	48
#16	34	42	35	42	35	43	36	44	38	45
#30	27	36	28	37	29	37	29	38	31	40
#40	21	31	22	32	23	32	24	37	25	35
#50	15	26	16	27	17	28	18	28	20	30
#100	7	19	8	20	9	21	10	21	12	24
#200	4	16	5	17	6	18	7	18	9	21

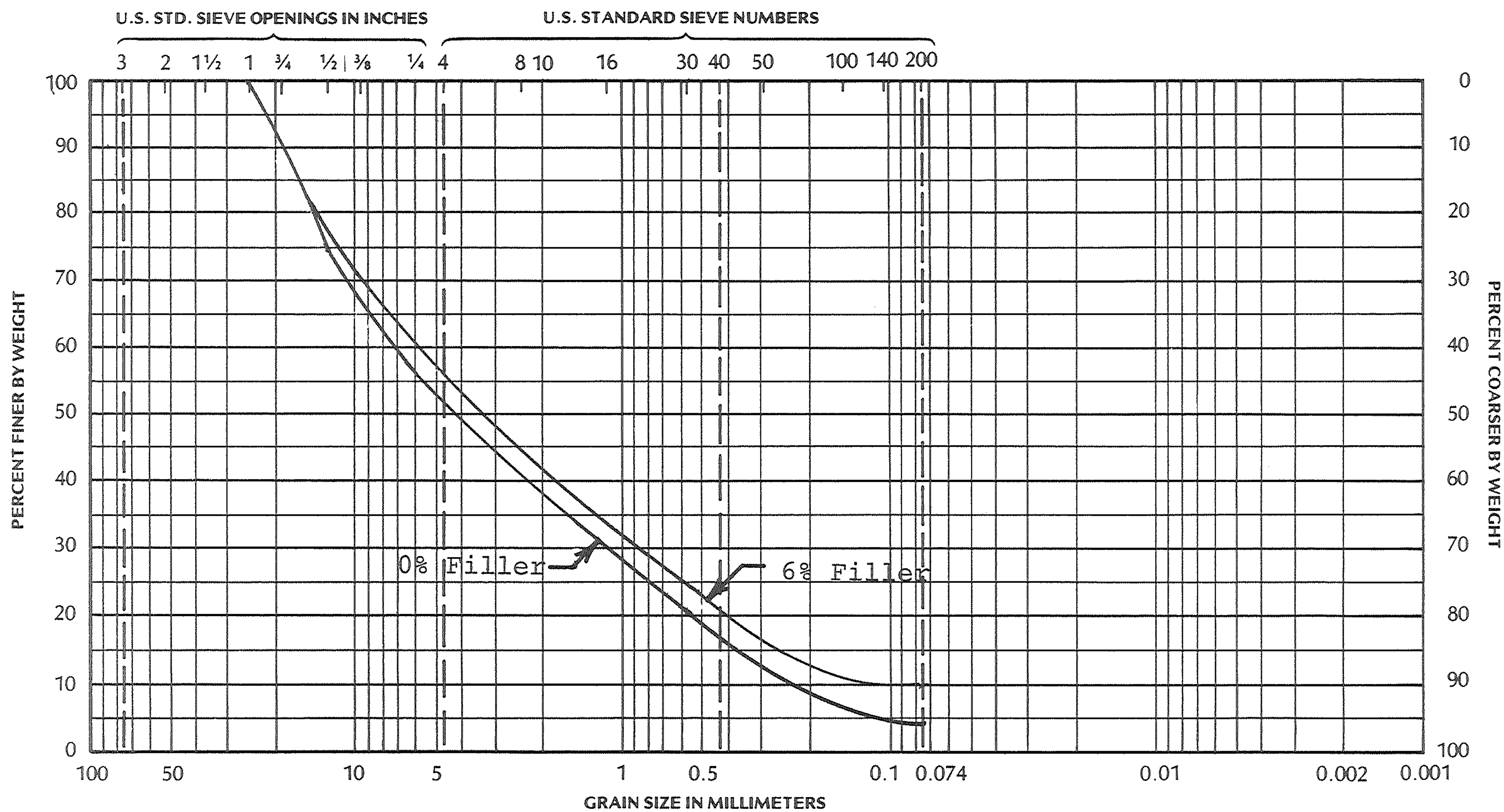

Figure 3. Gradations of Salt River Aggregate with up to 6% Filler.

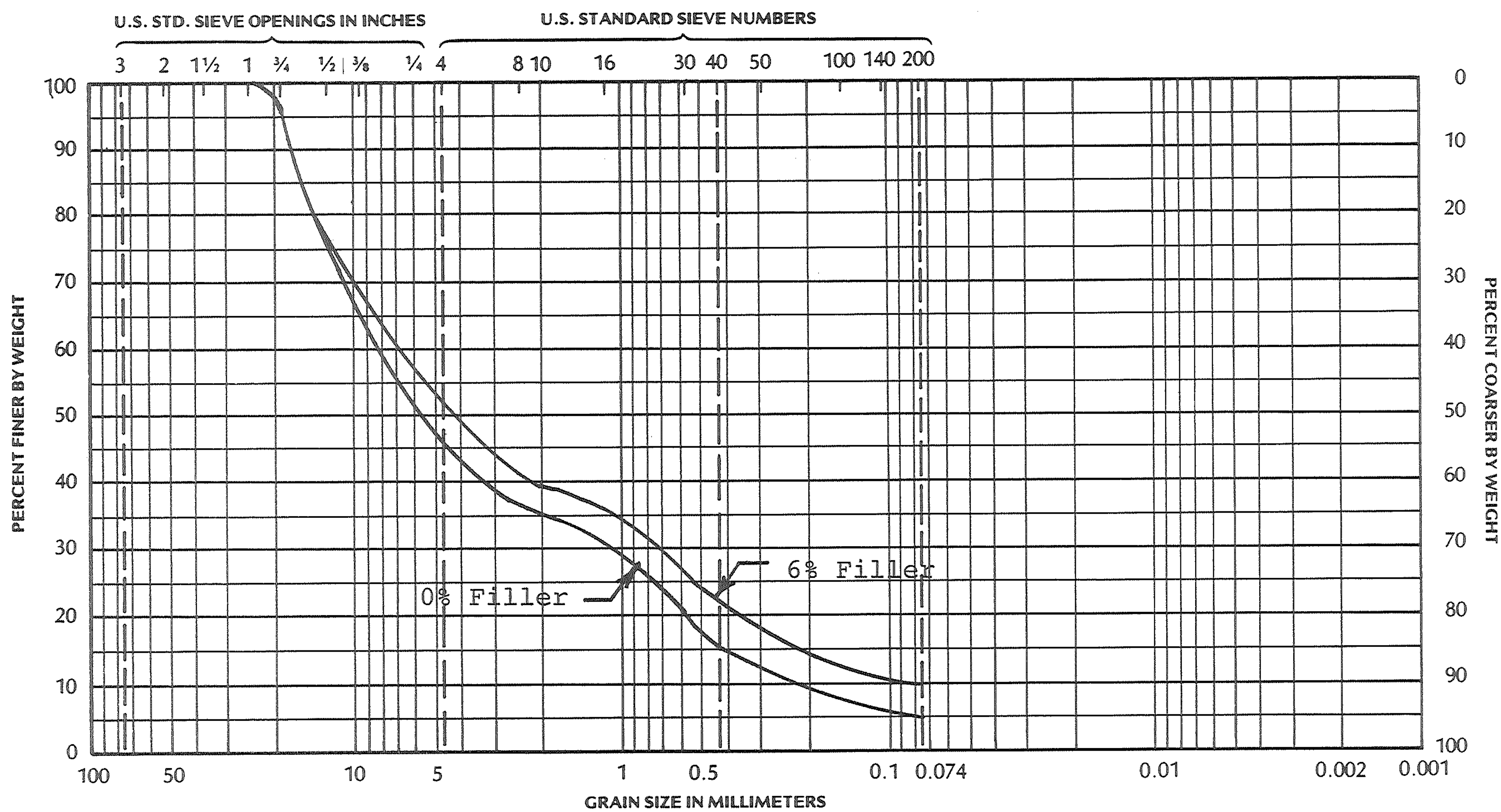

Figure 4. Gradations of Agua Fria Aggregate with up to 6% Filler.

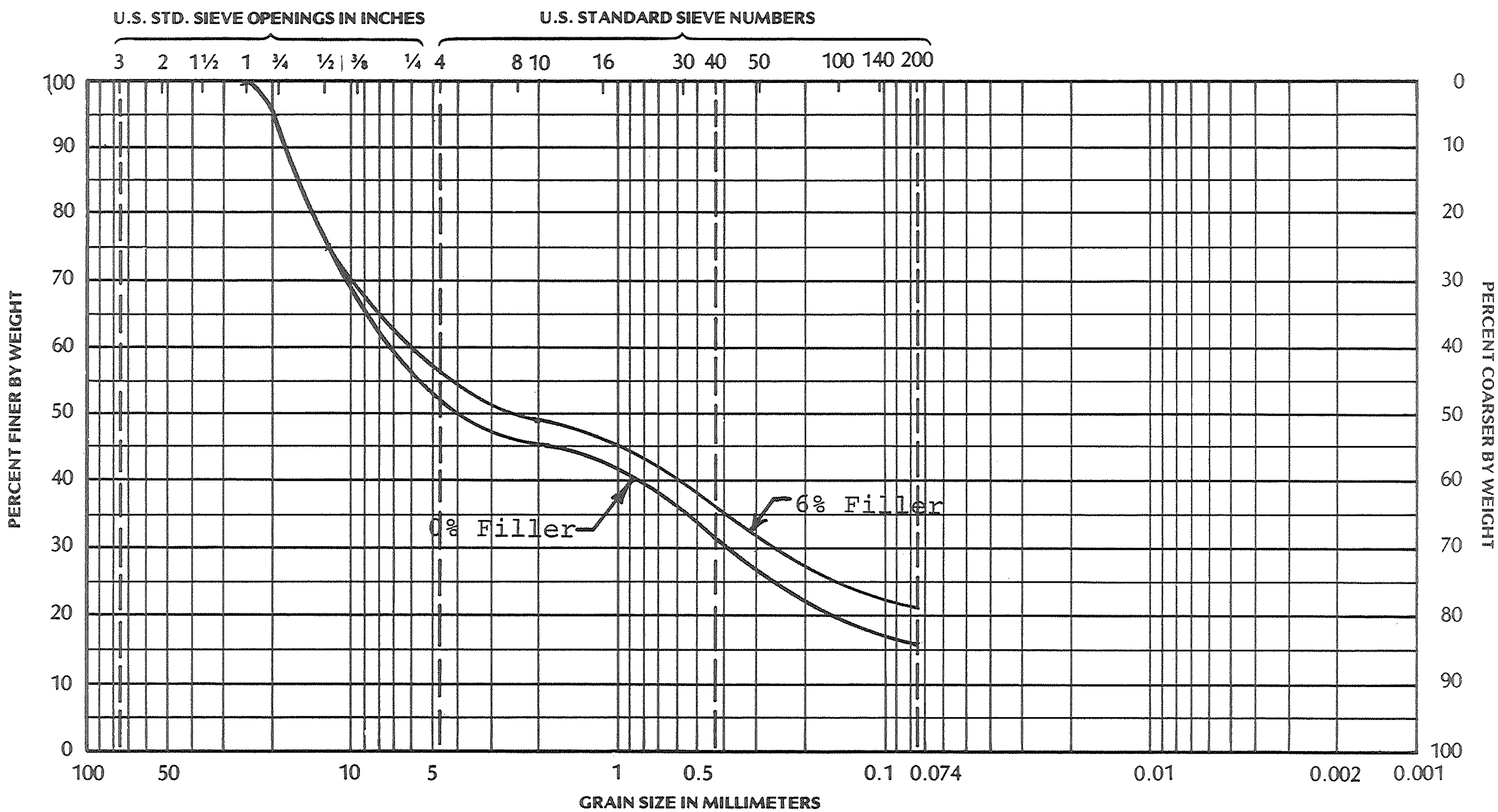

Figure 5. Gradations of Reidhead Aggregate with up to 6% Filler. (Washed Analyses)

Table 7 indicates both the specified dry gradations of Reidhead aggregate and actual gradations obtained using washed sieve analyses.

5.1.3 Specimens were batched and mixed in 3600 gm. batches. Following mixing, three 1200 gm. portions were obtained and compacted using 75 blows per side mechanical Marshall compaction. Mixing temperature was 280°F and specimens were compacted at 270°F.

5.1.4 Following extraction from compaction molds, specimens were subjected to density-voids and stability-flow analyses using the following procedures:

- Bulk Specific Gravity - ASTM D2726-73

- Maximum Theoretical Specific Gravity

  -Salt River and Reidhead Mixtures - ASTM D2041-78.

  -Agua Fria Mixtures - calculated using aggregate virtual specific gravity and specific gravity of asphalt cement due to variability noted with D2041-78 results with Salt River and Reidhead mixtures.

- Stability-Flow - ASTM 1559-76

5.1.5 Design asphalt contents for each mixture were selected to provide 4.0±0.5 percent air voids while meeting other mixture design criteria - stability, flow, and V.M.A. In several cases, it was necessary to select design asphalt contents which would provide air voids outside the set limits so that other criteria were met.

5.1.6 Mixture design data for each mixture combination investigated are presented in tabular and graphical form in Appendix A.

5.2 Immersion-Compression Testing

5.2.1 Immersion-compression testing in accordance with ADOT Method of Test 802C, "Effect of Water on Cohesion of Compacted Treated & Untreated Bituminous Mixtures" was performed on mixtures at design asphalt contents in order to investigate moisture resistance characteristics. In variance with the referenced test method, the retained strength is presented as a percentage of the dry strength of the treated material rather than the dry strength of the untreated material. Specimen fabrication and testing was performed at random and was replicated.

5.2.2 Summaries of properties of mixtures investigated at design asphalt contents are tabulated in Tables 8, 9, and 10.

Table 8 Summary of Properties of Salt River Mixtures at Design Asphalt Content

PROPERTY	SALT RIVER AGGREGATE — MIX DESIGNATION																
	MF	PB	2C	2L	1N	3N	6N	1P	3P	6P	½C5N	½C2P	1L5N	1L2P	2KD	CPRL	CPRH
Design Asphalt Content, %	5.50	5.85	5.00	5.30	5.60	5.40	4.50	6.00	5.10	4.90	5.25	5.5	4.75	4.70	5.65	5.95	6.40
Air Voids, %	4.0	4.0	4.0	4.2	4.0	3.8	3.5	4.2	4.0	4.2	3.8	3.9	4.1	4.2	4.0	5.0	3.8
V.M.A., %	16.0	16.0	15.0	14.6	14.6	14.2	13.1	15.2	15.0	14.0	13.8	14.6	13.2	15.0	15.6	16.2	17.0
V.F.W.A., %	75	70	73	68	73	77	73	76	72	65	75	73	68	70	73	75	80
Unit Weight, pcf	145.5	146.0	148.1	147.7	148.2	149.0	148.2	148.0	147.7	148.6	148.1	148.3	148.0	146.0	147.1	145.0	147.0
Effective Asphalt, %	5.2	4.9	4.6	4.3	4.6	4.6	4.1	4.7	4.6	3.8	4.4	4.5	3.8	4.6	4.9	5.2	5.8
Film Thickness (μM)	11.4	10.6	8.0	7.4	8.8	7.5	5.2	9.2	7.3	4.8	8.5	9.9	6.7	7.3	8.6	10.2	8.0
Dust/Asphalt Ratio	0.73	0.68	1.20	1.13	0.89	1.30	2.22	0.83	1.37	2.04	1.81	1.18	2.11	1.49	1.06	1.20	1.57
Stability, lbs.	1950	1700	1600	1850	1850	2100	2100	1650	1850	1820	2500	2600	2600	2250	2000	2850	5700
Flow, 0.01"	9	9	11	14	13	8	8	10	11	12	13	14	10	16	8	9	11
ADOT 802C 1 Comp. Strength																	
Dry (psi.)	530	603	496	540	473	524	590	501	574	566	604	586	646	547	582	785	1313
Wet (psi.)	284	414	400	340	364	337	520	421	496	546	508	463	580	435	359	547	848
Ret. Str., %	54	69	81	63	77	64	88	84	86	96	84	79	90	79	62	70	65
2 Comp. Strength																	
Dry (psi.)	481	477	479	605	499	537	581	503	493	560	585	550	683	634	446	1130	1281
Wet (psi.)	287	353	396	463	270	369	548	350	484	538	579	427	633	479	348	675	732
Ret. Str., %	60	74	83	77	54	69	94	70	98	96	99	78	93	76	78	60	57

Table 9 Summary of Properties of Aqua Fria Mixtures at Design Asphalt Content

AGUA FRIA AGGREGATE																			
			MIX DESIGNATION																
PROPERTY			NF	PB	2C	2L	1N	3N	6N	1P	3P	6P	½C5N	½C2P	1L5N	1L2P	2KD	CPRL	CPRH
Design Asphalt Content; %			5.20	5.30	5.00	5.00	5.40	4.60	4.30	5.20	4.80	4.00	4.20	4.90	4.20	4.80	5.40	6.00	6.50
Air Voids; %			4.0	4.0	4.0	4.0	4.0	4.2	4.0	4.0	4.0	4.2	3.9	4.0	4.1	4.0	4.1	4.0	6.0
V.M.A.; %			14.3	14.5	14.2	14.0	15.0	12.9	12.2	14.6	13.5	11.7	12.0	19.0	12.2	13.8	14.6	14.0	17.9
V.F.W.A.; %			76	75	73	73	78	72	78	75	74	70	72	77	70	75	75	78	65
Unit Weight; pcf			148.3	148.1	149.2	148.3	147.7	148.9	149.2	148.3	149.3	150.9	150.0	149.0	149.0	149.0	148.0	150.2	147.7
Effective Asphalt; %			4.3	4.4	4.1	4.1	4.5	3.7	3.5	4.3	3.9	3.2	3.4	4.0	3.3	3.9	4.5	5.1	5.6
Film Thickness; (μM)			8.6	9.1	7.0	7.0	8.4	5.7	4.4	8.1	6.0	4.0	4.4	6.6	4.5	6.1	7.6	9.4	9.9
Dust/Asphalt Ratio			0.88	0.87	1.32	1.32	1.04	1.65	2.47	1.08	1.58	2.65	2.40	1.45	2.52	1.58	1.22	0.77	0.71
Stability; lbs.			3300	2850	2800	2700	3300	2950	5000	3200	3450	3000	3200	2400	3700	3300	3300	4500	5600
Flow; 0.01"			12	13	12	13	14	12	12	13	13	11	10	11	12	13	13	13	10
ADOT 802C	1	Comp. Strength																	
		Dry; (psi.)	320	278	461	543	357	447	393	375	382	477	494	457	648	449	465	995	1038
		Wet; (psi.)	94	162	188	178	134	83	132	90	111	132	156	151	298	181	162	559	863
		Ret. Strength; %	29	58	41	33	38	19	34	24	29	28	32	33	46	40	35	56	83
	2	Comp. Strength																	
		Dry; (psi.)	497	296	546	370	461	513	689	382	534	605	439	410	640	436	506	938	1045
		Wet; (psi.)	131	154	220	167	159	123	287	87	170	246	173	159	358	175	191	765	693
		Ret. Strength; %	26	52	40	45	34	24	42	23	32	41	39	39	56	40	38	82	66

Table 10 Summary of Properties of Reidhead Mixtures at Design Asphalt Content

PROPERTY	NF	PB	2C	2L	1N	3N	6N	1P	3P	6P	½C5N	½C2P	1L5N	1L2P	2KD	CPRL	CPRH
	REIDHEAD AGGREGATE — MIX DESIGNATION																
Design Asphalt Content; %	6.00	6.00	6.50	6.50	6.50	6.50	6.50	6.50	6.50	7.00					7.00		
Air Voids; %	3.1	5.2	3.4	4.1	6.9	5.9	3.8	5.3	4.2	2.6					4.1		
V.M.A.; %	15.4	16.6	17.4	18.0	17.7	17.1	17.0	16.6	16.5	16.5					17.5		
V.F.W.A.; %	80	72	80	78	68	66	83	68	75	84					77		
Unit Weight; pcf	143.7	141.7	141.7	141.1	138.3	141.3	140.3	142.6	142.7	143.9					142.1		
Effective Asphalt; %	5.5	5.1	6.3	5.8	4.8	5.1	6.2	5.0	5.5	6.1					6.0		
Film Thickness; (µM)	4.8	4.4	5.0	4.7	4.1	4.1	4.5	4.3	4.5	4.4					4.9		
Dust/Asphalt Ratio	2.67	2.67	2.77	2.77	2.62	2.76	3.23	2.62	2.77	3.00					2.57		
Stability; lbs.	1600	1450	2850	1150	1700	1400	1200	1650	1700	1500					1450		
Flow; 0.01"	17	15	17	25	13	17	25	19	19	25					17		
ADOT 802C — 1 — Comp. Strength																	
Dry; (psi.)	534	606	438	926	572	262	662	590	266	560					482		
Wet; (psi.)	TWT*	89	TWT	TWT	TWT	TWT	TWT	TWT	16	TWT					70		
Ret. Strength; %	0	15	0	0	0	0	0	0	6	0					15		
2 — Comp. Strength																	
Dry; (psi.)	564	550	746	758	580	558	292	534	324	632					550		
Wet; (psi.)	53	TWT	TWT	TWT	TWT	TWT	TWT	TWT	TWT	TWT					TWT		
Ret. Strength; %	9	0	0	0	0	0	0	0	0	0					0		

*Note: TWT - Too weak to test.

6.0 DATA ANALYSIS

6.1 Mix Design Data

Statistical analysis of data generated during the mixture design phase of the laboratory study is not possible because this phase was not replicated.

6.1.1 Design asphalt content, stability, and flow data is tabulated and presented in ordered graphical form in Appendix B.

6.2 Immersion-Compression Data

Immersion-compression data generated during the laboratory phase of the investigation was analyzed using conventional two-way analysis of various techniques. Cell variance was checked and found to be homogeneous using the Foster and Burr Q-test (25).

Model:

$$Y_{ijk} = \mu + M_i + A_j + (MA)_{ij} + \varepsilon_{(ij)k}$$

in which:

Y_{ijk} = Response

μ = Overall mean

M_i = Effect of mixture (filler)

A_j = Effect of aggregate source

$(MA)_{ij}$ = Effect of mixture-aggregate interaction

$\varepsilon_{(ij)k}$ = Experimental error

k = Replication term

Source	df
M_i	16
A_j	1
$(MA)_{ij}$	16
Error	34
Total	67

The experiment test matrix is shown in Figure 6. Effects found to be significant in the analysis of variance were then ranked, using the Newman-Keuls multiple range test (26).

FIGURE 6 Test Matrix

Aggregate Source (A_j)
Mix Designation (M_i)

	NF	PB	2C	2L	1N	3N	6N	1P	3P	6P	½C5N	½C2P	1L5N	1L2P	2KD	CPRL	CPRH
SALT RIVER	=	=	=	≡	=	=	=	=	=	=	=	=	=	=	=	=	=
AGUA FRIA	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=

6.2.1 Density, air voids, dry strength, retained strength, and wet strength data obtained during immersion compression testing and subsequent analyses are tabulated and plotted in Appendix C. Data for mixtures containing Reidhead aggregate was not used in analyses due to its inconclusive nature, but is included for reference.

7.0 DISCUSSION

7.1 Mixture Design Properties

Comparison summaries of mixture design properties are tabulated in Tables 11, 12 and 13. In these tables, design properties for each mixture investigated are compared to the corresponding value for mixtures containing only natural fines.

7.1.1 Design Asphalt Content; Reference: Appendix B, Table B1, Figures B1, B2 and B3.

7.1.1.1 Salt River and Agua Fria Mixtures

Mixtures which contained high additive concentrations, (3 to 6 percent) contained less asphalt cement at the design asphalt content than mixtures containing only natural fines for both aggregate sources. Design asphalt contents for mixtures containing 1 to 2 percent additive were approximately the same as for mixtures containing only natural fines. Mixtures made with clear plant residue contained more sulfur-extended asphalt binder at the design asphalt content than mixtures containing only natural fines.

Reduced design asphalt contents for mixtures containing high filler-additive concentrations (3 to 6 percent), are believed to be the result of

Table 11. Comparison of Mix Properties to Those of Natural Fines

SALT RIVER AGGREGATE

Property \ Mix Designation	NF	PB	2C	2L	1N	3N	6N	1P	3P	6P	½C5N	½C2P	1L5N	1L2P	2KD	CPRL	CPRH
Design A.C.,%	●	H*	L	L	H	L	L	H	L	L	L	S	L	L	H	H	H
Stability,lbs	●	L	L	L	L	H	H	L	L	L	H	H	H	H	S	H	H
Flow,1/100 in	●	L	H	H	H	L	L	H	H	H	H	H	H	H	L	S	H
V.M.A.,%	●	S	L	L	L	L	L	L	L	L	L	L	L	L	L	H	H

Table 12. Comparison of Mix Properties to Those of Natural Fines

AQUA FRIA AGGREGATE

Property \ Mix Designation	NF	PB	2C	2L	1N	3N	6N	1P	3P	6P	½C5N	½C2P	1L5N	1L2P	2KD	CPRL	CPRH
Design A.C.,%	●	H	L	L	H	L	L	H	L	L	L	S	L	L	H	H	H
Stability,lbs	●	L	L	L	L	L	H	L	H	L	S	L	H	S	S	H	H
Flow,1/100 in.	●	H	S	H	H	S	S	H	H	L	L	L	S	H	H	H	L
V.M.A.,%	●	H	L	L	H	L	L	H	L	L	L	L	L	L	H		H

Table 13. Comparison of Mix Properties to Those of Natural Fines

REIDHEAD AGGREGATE

Property \ Mix Designation	NF	PB	2C	2L	1N	3N	6N	1P	3P	6P	½C5N	½C2P	1L5N	1L2P	2KD	CPRL	CPRH
Design A.C.,%	●	S	H	H	H	H	H	H	H	H					H		
Stability,lbs.	●	L	H	L	H	L	L	H	H	L					L		
Flow,1/100 in.	●	L	S	H	L	S	H	H	H	H					S		
V.M.A.,%	●	H	H	H	H	H	H	H	H	H					H		

*Note:

● Datum

H indicates greater value

S indicates the same value

L indicates lower value

two factors. First, these mixtures had lower V.M.A. levels than mixtures containing less filler which would result in a lesser volume of asphalt required for obtaining desired air voids. Second, addition of fillers may extend asphalt cement, as a result of binder volume extensions, due to encapsulation of filler producing mixtures which seem to contain increased binder quantities.

7.1.1.2 Reidhead Mixtures Design asphalt contents for Reidhead mixtures containing fillers were greater than for mixtures containing only natural fines. This trend is believed to be related to the high fines content of the Reidhead mixtures. Reidhead mixtures had greater design asphalt contents than either Salt River or Agua Fria mixtures.

7.1.2 Stability; Reference: Appendix B, Table B2, Figures B4, B5, and B6.

Mixtures containing clear plant residue had stabilities which were much higher than mixtures containing only natural fines. Mixtures containing Agua Fria aggregate produced higher stabilities than those containing Salt River aggregate. This may be due to different particle shapes of the two aggregates. All mixtures produced stabilities in excess of the required minimum (750 lb.) for acceptable paving mixtures according to MS-2 (25).

No other trends could be identified in the data.

7.1.3 Flow; Reference: Appendix B, Table B3, Figures B7, B8, and B9.

7.1.3.1 <u>Salt River and Agua Fria Mixtures</u> Flow values for all mixtures were within limits (8 to 16) required for acceptable asphalt concrete pavements (25). Mixtures containing Salt River aggregate has a greater range of flow values (8 to 16) than mixtures containing Agua Fria aggregate (10 to 14).

7.1.3.2 <u>Reidhead Mixtures</u> All mixtures investigated except those containing Pave Bond Special and 1 percent Navajo ash produced flow values which were in excess of acceptable limits (greater than 16). It is believed that the high fines content of Reidhead mixtures may be related to high flows.

7.1.4 V.M.A.; Reference: Appendix B, Table B4, Figures B10, B11, and B12.

7.1.4.1 <u>Salt River and Agua Fria Mixtures</u> V.M.A. values for all mixtures containing greater than 2 percent filler were lower than those for mixtures containing only natural fines. This result could be anticipated by considering that fillers occupy voids between aggregate particles. V.M.A. values for Agua Fria mixtures containing high amounts of filler (6 percent) were lower than the allowable minimum value of 13 (25). This could be corrected by slight gradation modifications.

7.1.4.2 <u>Reidhead Mixtures</u> V.M.A. values for all mixtures containing filler were higher than that of the mixture containing natural fines.

7.1.5 Based on the preceding discussions, it is concluded that for the aggregates investigated, asphalt concrete mixtures with acceptable mixture design properties can be produced using up to 6 percent fly ash by weight of mix. Differences which may exist in mixtures containing high amounts of fly ash filler are:

- Reduced design asphalt content
- Lower V.M.A. values

Since this portion of the experiment was not replicated, the preceding statement should be regarded as preliminary.

7.2 Immersion-Compression Results

Dry compressive strength, wet compressive strength and percent retained strength data obtained during immersion-compression testing yielded information on the effectiveness of the filler-additives as anti-stripping agents. Additionally, air voids and density data obtained for immersion-compression specimens are discussed due to their influence on mixture permeability and the stripping problem.

In the following discussions, only data for the Salt River and Agua Fria aggregate are considered due to the high degree of moisture sensitivity of the Reidhead aggregate. Reidhead data is not included in statistical analyses.

7.2.1 Density; Reference: Appendix C, Tables C1 and C2, Figures C1 and C2.

7.2.1.1 Two-way ANOVA* shows that mixtures and aggregate-mixture interaction are significant effects at the 0.01 level. Aggregate alone is not a significant effect at the 0.05 level.

*Analysis of Variance

7.2.1.2 Subsequent Newman-Keuls analysis shows that densities of Agua Fria CPRH (150.0 pcf), CPRL (150.1 pcf) and Salt River. 6P (148.9 pcf) mixtures are greater than for all other mixtures investigated. Though not significantly greater, the densities of Salt River CPRH (147.0 pcf) and CPRL (146.9) mixtures are highly ranked (Figure C1). High densities for mixtures containing clear plant residue are believed to be a result of two factors:

- High specific gravity of the filler (3.054)

- Reductions in binder viscosity due to sulfur extension of the asphalt thus permitting greater degrees of compaction using the same compactive effort. This tends to be supported by considering air voids data for immersion-compression specimens (Figures C3 and C4). Air voids of mixtures containing clear plant residue rank among the lowest of all mixtures investigated.

7.2.1.3 Densities of most other mixtures were found to be the same.

7.2.1.4 Other trends in the data worthy of discussion were not identified.

7.2.2 Air Voids; Reference: Appendix C, Tables C3 and C4, Figures C3 and C4.

7.2.2.1 Two-way ANOVA shows that mixtures and aggregate-mixture interaction are significant at the 0.01 level. Aggregate alone is not significant at the 0.05 level.

7.2.2.2 Subsequent Newman-Keuls analysis showed where significant differences existed in the air voids data, but no trends could be identified in the data.

7.2.2.3 It is believed that the inconclusive nature of the air voids data can be explained by considering mixture and binder stiffness modifications caused by fillers and additives. As previously discussed in (Section 7.2.1.2), at mixing and compaction temperatures, sulfur-extended asphalts with up to 35 percent replacement by weight exhibit lowered viscosities (23). Lowered binder viscosity may permit increased mixture densification during compaction resulting in lowered air voids. Mineral fillers, on the other hand, have been reported to increase binder stiffness (27) which, for a given compactive effort, could tend to result in less densification and greater air voids. Considering binder extensions by filler additions, increased densification and lower air voids may result from increases in apparent binder volume causing a greater degree of mix lubrication. The spherical shape of fly ash particles may also tend to lubricate the mixture, permitting increased densification.

Thus, it appears that several conflicting mechanisms may be functioning and influencing mix densification during compaction and resulting air voids.

7.2.2.4 It is interesting to note that the immersion-compression test specimens contained different levels of air voids than mixture design specimens ($4.0 \pm 0.5\%$) and that air voids in immersion-compression specimens varied from a high of 7.8 percent to a low of 3.2 percent. Densities of immersion-compression specimens were also less than densities obtained during mixture designs for specimens at design asphalt contents. These differences are believed to be influenced by two factors:

- The differing compactive modes and effort (Marshall is impact, immersion-compression is gradually increasing static).

- Modifications in binder and mix stiffness due to additions of filler, (Section 7.2.2.3).

The present immersion-compression test procedure (ADOT 802C) does not consider possible variations in mixture density and air voids. It is thus suggested that the effect of air voids in immersion-compression test specimens on test results be further considered or investigated.

7.2.3 Dry Compressive Strength; Reference: Appendix C, Tables C5 and C6, Figures C5 and C6.

7.2.3.1 Two-way ANOVA shows that both aggregate and mixture are significant effects at the 0.01 level. Aggregate-mixture interaction is not significant at the 0.05 level.

7.2.3.2 Subsequent Newman-Keuls analysis showed that for both Salt River and Agua Fria aggregate, mixtures containing clear plant residue had the highest dry compressive strengths of all mixtures investigated. (CPR mixtures - 1065 psi mean; all other mixtures - 496 psi mean). Dry compressive strengths of Salt River mixtures (overall mean - 599 psi) were higher than those of Agua Fria mixtures (overall mean 525 psi).

7.2.3.3 Newman-Keuls analysis also revealed that at the 0.05 level, mixtures containing cement, lime, Navajo fly ash, Pueblo fly ash, and kiln dust produced compressive strengths which were not greater than each other for both Salt River and Agua Fria aggregates.

7.2.4 Percent Retained Strength; Reference: Appendix C, Tables C7 and C8, Figures C7 and C8.

7.2.4.1 Two-way ANOVA shows that aggregate, mixture, and aggregate-mixture interaction are significant effects at the 0.01 level. With data for CPRL and CPRH mixtures removed from the analysis, all effects remained significant at the 0.01 level. The aggregate-mixture interaction indicates that the effectiveness of filler additives for improving percent retained strength was different for the different aggregates. This effect has been noted by others (28).

7.2.4.2 Subsequent Newman-Keuls analysis revealed that for most mixtures investigated, those containing Agua Fria aggregate had lower percent retained strengths than those containing Salt River aggregate, (67 percent mean for Salt River mixtures, 39 percent for Agua Fria mixtures), indicating that the Agua Fria aggregate was more moisture susceptible than Salt River aggregate. All Salt River mixtures provided mean retained strengths which were greater than the generally accepted minimum value of 50 percent. For Agua Fria aggregate, only additions of CPRL, CPRH, PB, and 1L5N increased percent retained strengths to above 50 percent.

7.2.4.3 The Newman-Keuls analyses was used to compile Tables 14 and 15 which indicate filler additives investigated which resulted in significantly (0.05 level) higher or lower percent retained strength results than the following mixtures:

- NF
- 2C
- 2L
- PB
- 6N
- 6P

Table 14 Comparison of % Retained Strength of Salt River Mixtures Investigated

Reference Mix Type	Mixtures with Results Significantly (0.05 Level) Higher or Lower Than Reference Mix: Higher	Lower
NF	6N,½C5N,1L5N, 3P,6P	–
2C	–	–
2L	6P	–
PB	–	–
6N	–	CPRL,CPRH,NF
6P	–	2L,2KD,3N,1N, CPRL,CDRH,NF
2KD	6P	–
CPRL	6N,½C5N,1L5N, 3P,6P	–
CPRH	6N,½C5N,1L5N, 3P,6P	–

Table 15 Comparison of % Retained Strength of Aqua Fria Mixtures Investigated

Reference Mix Type	Mixtures with Results Significantly (0.05 Level) Higher or Lower Than Reference Mix: Higher	Lower
NF	PB,CPRL,CPRH	–
2C	CPRL,CPRH	–
2L	CPRL,CPRH	–
PB	–	NF,1P,3N
6N	CPRL,CPRH	–
6P	CPRL,CPRH	–
2KD	CPRL,CPRH	–
CPRL	–	2C,1L2P,2L,6N2KD,1N, ½C2P,½C5N,6P3P,NF,1P,3N
CPRH	–	2C,1L2P,2L,6N,2KD,1N, ½C2P,½C5N,6P,3P,NF,1P,3N

- 2KD
- CPRL
- CPRH

Salt River Mixtures The 6N, 1/2C5N, 1L5N, 3P, and 6P had significantly higher percent retained strengths than the NF mixture (57%). The 6P mixture had higher retained strength (96%) than the 2L, 2KD, 3N, 1N, CPRL, CPRH, and NF mixtures. The 6N, 1/2 C5N, 1L5N, 3P, and 6P mixtures had significantly higher retained strengths than either the CPRL or CPRH mixtures.

Agua Fria Mixtures The CPRL and CPRH mixtures had significantly higher retained strengths than all other mixtures except PB and 1L5N. The PB, CPRL, and CPRH mixtures had higher retained strength (55%) than the NF, 1P, or 3N mixtures.

7.2.5 Wet Compressive Strength; Reference: Appendix C, Tables C9 and C10, Figure C9 and C10.

7.2.5.1 Two-way ANOVA shows that aggregate, mixture, and aggregate-mixture interaction are significant effects at the 0.01 level. With data for CPRL and CPRH mixtures removed from the analysis, all effects remained significant at the 0.01 level. The interaction indicates that the effectiveness of filler-additives for improving wet strength was different for the different aggregates.

7.2.5.2 Subsequent Newman-Keuls analysis showed that except for mixtures containing clear plant residue, mixtures containing Salt River aggregate had higher mean wet strengths than mixtures containing Agua Fria aggregate, (overall means, Salt River - 464 psi, Agua Fria 217 psi). All Salt River mixtures had mean wet strengths over the required 150 psi minimum required by ADOT.

All Agua Fria mixtures except 1N, 3P, NF, 3N, and 1P had mean wet strengths over 150 psi.

7.2.5.3 The Newman-Keuls analyses was used to compile Tables 16 and 17 which indicate filler additives investigated which resulted in significantly (0.05 level) higher or lower mean wet compressive strengths than the following mixtures:

- NF
- 2C
- 2L
- PB
- 6N

Table 16 Comparison of Wet Compressive Strength of Salt River Mixtures Investigated

Reference Mix Type	Mixtures with Results Significantly (0.05 Level) Higher or Lower Than Reference Mix: Higher	Lower
NF	3P,6N,6P,½C5N 1L5N,CPRL,CPRH	-
2C	1L5N,CPRL,CPRH	-
2L	1L5N,CPRL,CPRH	-
PB	1L5N,CPRL,CPRH	-
6N	CPRH	2KD,3N,1N,NF
6P	CPRH	2KD,3N,1N,NF
2KD	6N,½C5N,1L5N,CPRL CPRH	-
CPRL	CPRH	2L,2C,1P,PB,2KD,3N, 1N,NF
CPRH	-	CPRL,1L5N,½C5N,6P,6N,3P, 1L2P,½C2P,2L,2C,1P,PB,2KD 3N,1N,NF

Table 17 Comparison of Wet Compressive Strength of Aqua Fria Mixtures Investigated

Reference Mix Type	Mixtures with Results Significantly (0.05 Level) Higher or Lower Than Reference Mix: Higher	Lower
NF	1L5N,CPRL,CPRH	–
2C	CPRH,CPRL	–
2L	CPRH,CPRL	–
PB	CPRH,CPRL	–
6N	CPRH,CPRL	–
6P	CPRH,CPRL	–
2KD	CPRH,CPRL	–
CPRL	–	1L5N,6N,2C,6P,1L2P,2KD,2L, ½C5N,PB,½C2P,1N,3P,NF 3N,1P
CPRH	–	1L5N,6N,2C,6P,1L2P,2KD,2L, ½C5N,PB,½C2P,1N,3P,NF 3N,1P

- 6P
- 2KD
- CPRL
- CPRH

Salt River Mixtures The 3P, 6N, 6P, 1/2C5N, 1L5N, CPRL, and CPRH mixtures had higher mean wet compressive strengths than the NF mixture (285 psi). The 1L5N, CPRL, and CPRH mixtures had higher strengths than the 2C, 2L, and PB mixtures. The 6N and 6P mixtures had higher strengths than the 2KD, 3N, 1N, and NF mixtures. The mean wet strength of the CPRH mixture (790 psi) was higher than those of all other Salt River mixtures.

Agua Fria Mixtures The 1L5N, CPRL, and CPRH mixtures had higher mean wet compressive strengths than the NF mixture (113 psi). The CPRH and CPRL mixtures had higher wet strengths than the 2C, 2L, PB, 6N, 6P, and 2KD mixtures. The CPRL and CPRH mixtures had higher wet strengths than all other Agua Fria mixtures.

7.2.6 Based on the preceding discussions, it is concluded that additions of various fillers including fly ash can be effective methods of improving the moisture resistance of asphalt concrete mixtures in the laboratory. In this study, with the materials investigated, filler-additives which were found to be most effective as anti-strip agents in the laboratory include:

- Clear plant residue (CPRL, CPRH)
- Pueblo fly ash (3P, 6P)
- Navajo fly ash (6N)
- Lime and Navajo ash (1L5N)

Several of the materials investigated performed as well as portland cement and hydrated lime in the testing program including:

- Clear plant residue (CPRL, CPRH)
- Pueblo fly ash (1P, 3P, 6P)
- Navajo fly ash (1N, 3N, 6N)
- Kiln dust (2KD)
- Combinations of cement, lime and fly ash (1L5N, 1L2P, 1/2C5N, 1/2C2P)

7.3 General Discussion

Two observations made during this study deserve further discussion:

- Filler-additive effectiveness with various aggregate sources to improve resistance to the effect of water.

- Air voids in immersion-compression test specimens.

7.3.1 Filler-Additive Effectiveness as Anti-Strips with Different Aggregates.

Percent retained strength and wet compressive strength data showed that the filler additives investigated in the study varied in effectiveness with the different aggregates. For example, additions of 6 percent Pueblo fly ash to Salt River aggregate improved percent retained strength from 57 percent to 96 percent, but with Agua Fria aggregate, the same filler addition only resulted in improvements from 27 percent to 35 percent. Other similar differences in filler-additive effectiveness (interactions) are found in the percent retained strength and wet compressive strength data. These aggregate-filler-additive interactions are depicted graphically in Figures 7 and 8. From Figures 7 and 8, it can be seen that CPRL and CPRH mixtures performed better with the Agua Fria aggregate than Salt River aggregate. ANOVA analyses with CPRL and CPRH data removed indicated that other aggregate-mixture interactions occurred in the percent retained strength (2C, 3N, 1/2C5N) and

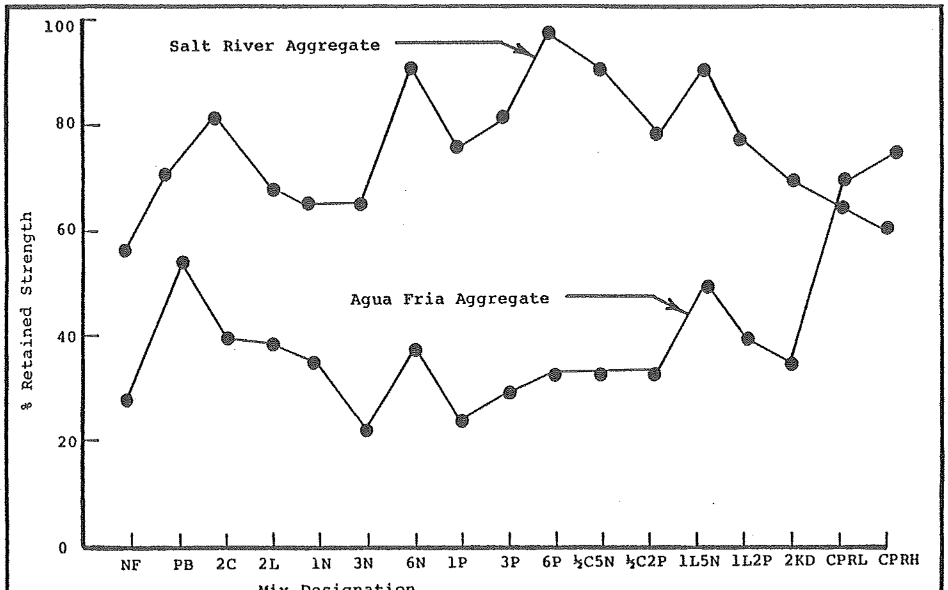

Figure 7

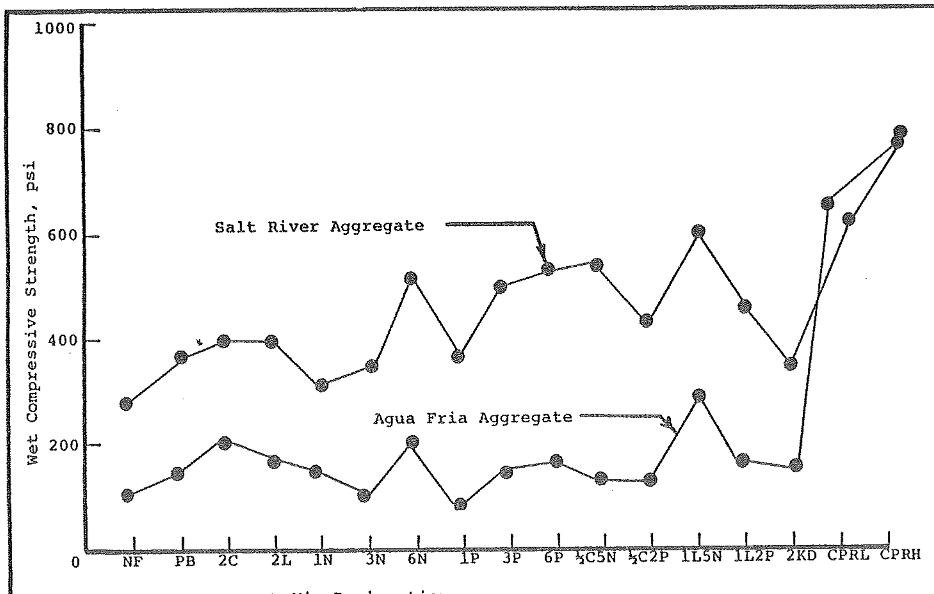

Figure 8

wet compressive strength (2C, 1/2C5N, 1/2C2P) data.

This suggests that the filler-additives investigated in this study, when used with various aggregates as anti-strips in asphalt concrete mixtures, may vary in effectiveness with different mixtures and will therefore need to be selected for different aggregate sources.

7.3.2 Air Voids in Immersion-Compression Specimens

As previously discussed (Section 7.2.2.4), air void levels and densities of immersion-compression specimens were different than those obtained at the design asphalt content during mixture designs. Differences are believed to be related to the different compaction modes and changes in mix workability or stiffness due to filler additions.

Air voids level is a factor which can influence the stripping problem. Asphalt concrete mixtures with high air voids are more permeable by water than mixtures with lower air voids. Mixtures with high air voids can allow more water to intrude into pavements and possibly increase the degree of water sensitivity of the mixture.

A test method for investigating moisture resistance of asphalt concrete which recently was developed after extensive laboratory and field research requires that air void levels in laboratory test specimens be controlled (29). If specimen voids are found to vary by more than 0.5% from the selected value, the specimen is discarded and a replacement fabricated.

Air void levels in immersion-compression test specimens for different mixtures investigated in this study varied from 3.2 percent to 7.8 percent - a spread of 4.6 percent. Considering the influence of air voids on the stripping problem, it is believed that this variation may have influenced percent retained strength and wet compressive strength test results for some of the filler-additives investigated in this study. The possibility exists that percent retained strength and wet strength results for mixtures which contained high air voids levels (greater than 6 percent) may have been better if air voids levels in immersion-compression test specimens had been lower (4 to 5 percent).

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